

Hygic material properties of porous building materials

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ABSTRACT: The erection of new building, the renovation and preservation of building structures and monuments requires the quantification of the temperature, moisture, salt and pollution distribution in porous materials. The thermophysical modelling leads to a coupled non-linear differential equation system. The temperature T and the capillary pressure p_c will be used as driving potentials in this transport system. In order to solve the transport equation system with modern numerical methods the material function thermal conductivity $\lambda(w(p_c), T)$, capillary conductivity $K(w(p_c), T)$ and vapour conductivity $\delta(w(p_c), T)$ and the moisture retention function $w(p_c, T)$ are necessary. This paper will be focused on the determination of $w(p_c)$ and $K(w(p_c))$ in the isothermic case. The pore size distribution has been formulated by simple analytical functions with w_j (partial volume of the pore segment), R_j (mean radius of the pore segment) and n_j (shape parameter). Hence, it follows by integration the retention function and the moisture conductivity with the same parameters. The results will be compared with measurement results of the "HAMSTAD-project" materials.

1 MODELLING

The modelling of the coupled heat and moisture transfer can be expressed by the following non linear differential equation system for the calculation of temperature and moisture fields in building materials and building structures (Häupl, 87), (Grunewald, 98), (Künzel, 94), (Funk, 02), (Bomberg, 02).

heat transfer

$$\begin{aligned} & \frac{\partial}{\partial t} \left[(\rho_M c_M + \rho_w c_w w) \cdot T + (\rho_v c_{pV} + \rho_A c_{pA}) \cdot (w_s - w) T + \right. \\ & \left. \rho_v h_v (w_s - w) - u_{source} \right] \\ &= \frac{\partial}{\partial x_k} \left[\left(\lambda + \delta e^{-\frac{p_c}{\rho_w R_v T}} (h_v + c_{pV} T) \cdot \left[\frac{\partial p_s}{\partial T} + \frac{p_s p_c}{\rho_w R_v T^2} \right] \right) \frac{\partial T}{\partial x_k} + \right. \\ & \left. \left(K c_w T + \delta e^{-\frac{p_c}{\rho_w R_v T}} (h_v + c_{pV} T) \cdot \frac{p_s}{\rho_w R_v T} \right) \frac{\partial p_c}{\partial x_k} \right] \end{aligned} \quad (1)$$

moisture transfer

$$\begin{aligned} & \frac{\partial}{\partial t} [(\rho_w w + \rho_v (w_s - w)) - \rho_{w,source}] \\ &= \frac{\partial}{\partial x_k} \left[\left(K + \delta e^{-\frac{p_c}{\rho_w R_v T}} \frac{p_s}{\rho_w R_v T} \right) \frac{\partial p_s}{\partial x_k} + \right. \\ & \left. \delta e^{-\frac{p_c}{\rho_w R_v T}} \left(\frac{\partial p_s}{\partial T} + \frac{p_s p_c}{\rho_w R_v T^2} \right) \frac{\partial T}{\partial x_k} \right] \end{aligned} \quad (2)$$

The left hand side of the equations (1) and (2) contains the time derivation of the storage functions for heat and moisture, the right sides are the divergences of the heat and moisture flow densities. As driving potentials the temperature T and the capillary pressure p_c – that means actual thermodynamic potentials – have been used. The capillary pressure p_c and the vapour pressure p_v correspond with the waterfilled pore radius by the well known equations (3) and (4).

$$p_c = \frac{2\sigma}{r} \quad p_v = p_s(T) e^{-\frac{2\sigma}{r \cdot \rho_w \cdot R_v \cdot T}} \quad (3), (4)$$

In order to solve the transport equation system (1) and (2) by given initial and boundary conditions (usually the hourly values of the climate components temperature, relative humidity, short- and longwave radiation, wind speed, wind direction and precipitation – driving rain), the material functions $c(w(p_c), T)$ and $w(p_c), T$ for the storage and $\lambda(w(p_c), T)$, $K(w(p_c), T)$ and $\delta(w(p_c), T)$ for the transport are necessary. This paper uses the definition and determination of the moisture storage function $w(p_c)$ and the liquid moisture conductivity $K(w(p_c))$ and the vapour transport function $\delta(w(p_c))$ in the isothermal case, though a lot of practical non isothermal cases with the DELPHIN code have been solved (Häupl, 99), (Häupl, 01), (Fechner, 01).

The fundamental idea is to represent the pore size distribution by means of a function with suitable parameters. The moisture storage function is given by a simple integration of the pore size distribution. The parameters can be identified by the measurement of the capillary pressure function with the pressure plate apparatus in the overhygroscopic range and the sorption isotherm in the hygroscopic range. The moisture transport functions can be formulated by means of the equilibrium of capillary pressure and friction pressure. In addition to the measurement of the storage function, the measurement of the moisture conductivity for saturated samples, the water uptake and water penetration coefficient and the water vapour coefficient μ for $\phi = 20\%$ and $\phi = 85\%$ is sufficient to determine the parameters of the transport function.

2 MOISTURE STORAGE FUNCTION

As criterion of the representation of the pore structure, the pore size distribution $f(r) = dw/dr$ or $f_p(r) = dw/d(\log r)$ will be used. It can be measured by mercury porosimetry, BET-method etc. For the analytical description of the pore size distribution the following formulations after a lot of tests were deemed good.

$$f_{pn}(r) = \sum_{j=1}^m \frac{4.6 \cdot \left(\frac{r}{R_j}\right)^2 w_{nj} (n_j - 1)}{\left[1 + \left(\frac{r}{R_j}\right)^2\right]^{n_j}} \quad (5)$$

The first one contains the partial volume w_{sj} and the main radius R_{oj} of the pore size compartment as parameters, the second equation needs also this parameters (now w_{nj} and R_j) but in addition the shape parameter n_j describing the width of the distribution function. In general $m = 3$ or $m = 4$ packages are sufficient (three or four modal models). Up to now about 20 building and insulation materials have been assessed. The moisture loading process up to the filled radius r can be described by the integration of (5) and (6), respectively.

$$w(r) = \int_0^r \frac{fp(r)}{r} 0.4343 dr \quad (6)$$

The integration of the equation (5) give (7)

$$w_n(r) = \sum_{j=1}^m \left[1 - \left(1 + \left(\frac{r}{R_j} \right)^2 \right)^{1-n_j} \right] w_{nj} \quad (7)$$

(7) look a bit like the formulation of van Genuchten (van Genuchten, 80). Hence, it follows with the capillary pressure (3)

$$w_n(p_c) = \sum_{j=1}^m \left[1 - \left(1 + \left(\frac{2\sigma}{p_c R_j} \right)^2 \right)^{1-n_j} \right] w_{nj} \quad (8)$$

In the last both equations the moisture content w in dependence on the capillary pressure p_c will be signified as moisture storage functions. In the overhygroscopic area ($p_c < 5 \cdot 10^6$ Pa) (8) is identical with the capillary pressure function, in the hygroscopic

area ($p_c > 5 \cdot 10^6$ Pa) (8) is identical with the sorption isotherm. The sorption isotherm follows by means of the equation (4).

$$p_c = -\rho_w R_v T \cdot \ln(\varphi) \quad (4)$$

$$w_n(\varphi) = \sum_{j=1}^m \left[w_{nj} \cdot \left(1 - \left(1 + \left(\frac{2\sigma}{\rho_w R_v T \cdot \ln(\varphi) R_j} \right)^2 \right)^{1-n_j} \right) \right] \quad (9)$$

The moisture storage functions can be measured and the simple parameters R_{oj} and w_{sj} or R_j and w_j can be identified (see example in chapter 4 and measurement results in (Plagge, 99)).

3 MOISTURE TRANSPORT FUNCTION

In the isothermal case, the equation (2) delivers for the liquid moisture flow density

$$g_w = -K_w(p_c) \text{grad } p_c, \quad K_w \text{ in s} \quad (10)$$

The driving potential is the capillary pressure p_c . $K_w(p_c)$ is the liquid moisture transport function or moisture conductivity. Under the presupposition of a bundle of parallel capillaries with gaps for the pressure compensation, the equilibrium between the capillary pressure and the friction pressure results in (compare (Krischer, 92))

$$g_w = \left[-\frac{\rho_w \cdot M}{8\eta} \left[\int_0^r f_p(r) r dr \right] \right] \text{grad } p_c \quad (11)$$

Hence it follows for $K_w(p_c)$

$$K_w(p_c) = +\frac{\rho_w \cdot M}{8\eta} \int_0^r f_p(r) r dr \quad (12)$$

In order to simulate a mesh of non regularly pores with different moisture transport resistances (Roels, 00), a lot of background calculations with different friction forces was done. The following method has been supported: The unknown details of the pore structure will be included by the measurement of moisture conductivity K_s for saturated samples by means of a small outside pressure difference p_o (Darcy-permeability). That means:

$$K_w(p_o) = -\frac{\rho_w M}{8\eta} \int_0^{r_o} f_p(r) r dr = K_s \quad (13)$$

$$p_o = \frac{2\sigma}{r_o} \quad (14)$$

The integration of the equations (12) and (13) is possible with the chosen formulation of the pore size distribution (5). This is the most important advantage compared to (van Genuchten, 80). From (12) and (13) with (5) it follows for the moisture conductivity formula (15)

$$K_{wn}(p_c) = K_s \cdot \frac{\sum_{j=1}^m \left[1 - \frac{1 + n_j \left(\frac{r}{R_j} \right)^2 + (n_j - 1) \cdot \left(\frac{r}{R_j} \right)^4}{\left[1 + \left(\frac{r}{R_j} \right)^2 \right]^{n_j}} \right] \cdot \frac{R_j^2 w_{nj}}{n_j - 2}}{\sum_{j=1}^m \left[1 - \frac{1 + n_j \left(\frac{r_o}{R_j} \right)^2 + (n_j - 1) \cdot \left(\frac{r_o}{R_j} \right)^4}{\left[1 + \left(\frac{r_o}{R_j} \right)^2 \right]^{n_j}} \right] \cdot \frac{R_j^2 w_{nj}}{n_j - 2}} \quad (15)$$

$$r = \frac{2\sigma}{p_c} \quad r_o = \frac{2\sigma}{p_o}$$

With the simple parameters R_{oj} (main radius of the pore segment), w_{sj} (partial volume of the pore segment) and K_s (Darcy-permeability) the liquid moisture conductivity in the whole range (from absolutely dry to completely saturated) can be formulated. Of course with (7) the moisture conductivity in dependence on the moisture content w can be represented, but unfortunately only implicitly. Chapter 4 shows results for the material ceramic brick.

In the next step the moisture conductivity K should be transformed into the moisture diffusivity D_w . It is defined by

$$g_w = -\rho_w D_w(w) \text{grad} w \quad (16)$$

The comparison of (16) with (11) gives for D_w

$$D_w(r) = 4.6 \cdot \frac{K_w(r)}{f_p(r)} \cdot \frac{\sigma}{r \rho_w} \quad (17)$$

Moreover the so called water uptake coefficient is well known and fixed in the ISO standard (EN ISO 15 148).

$$\frac{m_w}{A} = A_w \sqrt{t} \quad (18)$$

A sample will be contacted directly with the water surface. The increasing of the mass m_w per area A caused by the water penetration will be measured. Hence it follows A_w . It is also possible to measure the penetration depth x_E of the water front and consequently the water penetration coefficient

$$x_E = B \sqrt{t} \quad (19)$$

This simple experiment is suitable to control partially the storage and transport functions (7), (8), (15), (17) by the numerical simulation of the penetration fields with the DELPHIN (Grunewald, 98) code.

However, in this paper also a simplified analytical formulation for the moisture diffusivity D_w basing on the parameters (18) and (19) will be proposed. For the isothermal case and missing moisture sources the moisture transfer equation (1) reads as follows

$$\frac{\partial}{\partial t} w(x, t) = \frac{\partial}{\partial x} \left[D_w(w) \frac{\partial w}{\partial x} \right] \quad (20)$$

The driving potential p_c is substituted by the water content w . The formulation (21) has approximately the same shape like the function (19) – compare example in chapter 4.

$$D_{wu}(w) = D_o \left[\left(1 - \frac{w - w(\varphi_o)}{w_{sf} - w(\varphi_o)} \right)^{\frac{1}{k}-1} - \left(1 - \frac{w - w(\varphi_o)}{w_{sf} - w(\varphi_o)} \right)^{\frac{2}{k}} \right] \quad (21)$$

The analytical solution of the equation (20) with (21) for the simple water uptake experiment is given by (22)

$$w(x, t) = (w_{sf} - w(\varphi_o)) \left[1 - \left(\frac{1}{\sqrt{2D_o(k+1)}} \frac{x}{\sqrt{t}} \right)^k \right] + w(\varphi_o) \quad (22)$$

The moisture field can also be measured and the solution (22) can be confirmed.

The parameter D_o (moisture diffusivity for

$$w \approx \frac{w_{sf} - w(\varphi_o)}{2})$$

and k (shape parameter) in (21) can be calculated by means of the water uptake coefficient A_w and moisture penetration coefficient B .

For $w = w(\varphi_o)$ the equation (22) results the penetration depth x_E , and the time integration about the field (22) delivers the increasing of the whole moisture m_w/A . Hence it follows for k and D_o

$$k = \frac{A_w}{\rho_w (w_{sf} - w(\varphi_o)) B - A_w} \quad (23)$$

$$D_o = \left[\frac{A_w}{\rho_w (w_{sf} - w(\varphi_o))} \right] \frac{k+1}{2k^2} \quad (24)$$

The example in chapter 4 confirms this way. Of course the moisture diffusivity (21) can be transformed by means of (17) in the moisture conductivity and can be compared with (15). Finally the measurement of the vapour resistance coefficient μ should be integrated in this theory. In the μ -experiment, the relative humidity φ is the driving potential. The moisture will be transported as vapour and also as liquid water. The total moisture flow density is given by

$$g = -\rho_w \left[\frac{K_w}{\varphi} RT + \delta \frac{p_s}{\rho_w} \right] \text{grad } \varphi \quad (25)$$

with the total moisture transport function

$$K_\varphi = \frac{K_w}{\varphi} R_v T + \delta \frac{p_s}{\rho_w} \quad K_\varphi \text{ in } \frac{m^2}{s} \quad (26)$$

and

$$\delta = \frac{\delta_A}{\mu_o} \left(1 - \frac{w}{w_s} \right) \quad (27)$$

for the vapour transport function.

K_φ should be measured for defined relative humidities for example $\varphi=20\%$ (between 11,3% and 30%) and $\varphi=85\%$ (between 75% and 96.9%) and not between 0 and 50% (dry cup) and 50% and 95% (wet cup) – see (EN ISO 15 572).

If the gradient of p_c will be used as driving potential again (compare also (2)) the moisture flow density reads as follows

$$g = - \left[K_w(p_c) + \frac{\delta_A}{\mu_o} \left[1 - \frac{w(p_c)}{w_s} \right] \frac{p_s}{\rho_w R_v T} \cdot e^{-\frac{p_c}{\rho_w R_v T}} \right] \text{grad } p_c \quad (28)$$

$K_w(p_c)$ see (15), $w(p_c)$ see (8)

That means the total moisture conductivity is given by

$$K_w(p_c) + \frac{\delta_A}{\mu_o} \left[1 - \frac{w(p_c)}{w_s} \right] \frac{p_s}{\rho_w R_v T} \cdot e^{-\frac{p_c}{\rho_w R_v T}} \quad (29)$$

In the following chapter for the capillary active insulation material calciumsilicate (GLASGOW-material) all storage and transport function have been measured and calculated. This material was used for the improvement of the thermal resistance by an additional inside insulation of old buildings with worth preserving facade (Häupl, 99), (Häupl, 01).

4 EXAMPLE: MATERIAL CERAMIC BRICK

4.1 Basic physical parameters and material properties

surface tension of water	$\sigma = 0.074 \text{ N/m}$
viscosity of water	$\eta = 10^{-3} \text{ kg/ms}$
density of water	$\rho_w = 1000 \text{ kg/m}^3$
water vapour constant	$R = 462 \text{ Ws/kgK}$
temperatur	$T = 293 \text{ K}$
conductivity for saturated material	$K_s = 1.763 \cdot 10^{-8} \text{ s}$
water uptake coefficient	$A_w = 0.1458 \text{ kg/m}^2 \text{ s}^{1/2}$
vapour diffusion resistance factor for dry material	$\mu_0 = 18.5$

4.2 Water retention function $w(p_c)$

Table 1 shows the measured values for the water retention function. The values are measured by using of different measurement techniques (sorption experiments, pressure plate etc.).

Table 1. measured values

capillary pressure p_c (Pa)	moisture content w (m^3/m^3)	capillary pressure p_c (Pa)	moisture content w (m^3/m^3)
$10^{2.50}$	0.2450	$10^{6.63}$	0.0015
$10^{3.48}$	0.2334	$10^{6.74}$	0.0013
$10^{4.00}$	0.2297	$10^{7.15}$	0.0013
$10^{4.78}$	0.0697	$10^{7.36}$	0.0011
$10^{5.30}$	0.0126	$10^{7.58}$	0.0011
$10^{5.60}$	0.0099	$10^{7.87}$	0.0009
$10^{5.90}$	0.0087	$10^{8.18}$	0.0008
$10^{6.15}$	0.0082	$10^{8.47}$	0.0007

The parameters of the water retention function has been calculated by using a nonlinear approximation algorithm. In this case the exponent n of the function is always 3.

Table 2. coefficients of the water retention function (8)

j	w_{nj} (m^3/m^3)	R_i (m)	n_i (-)
1	0.0120	$1.14 \cdot 10^{-04}$	3
2	0.2247	$6.00 \cdot 10^{-06}$	3
3	0.0010	$1.30 \cdot 10^{-07}$	3
4	0.0073	$5.60 \cdot 10^{-10}$	3

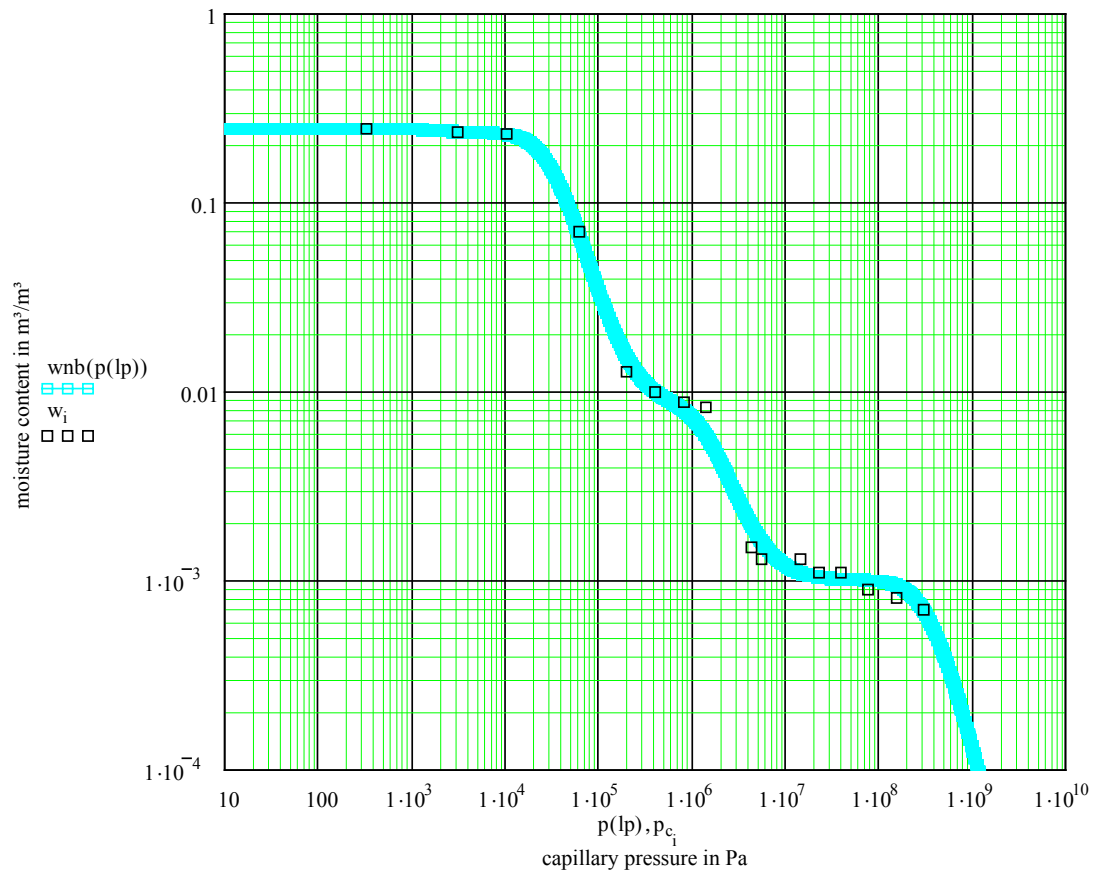


Fig. 1: Comparison of calculated and measured water retention function of the material ceramic brick

4.3 Pore size distribution $fp(r)$

The pore size distribution function (5) has been calculated by derivation of the moisture retention function (8). The parameters of this function is given by Table 2.

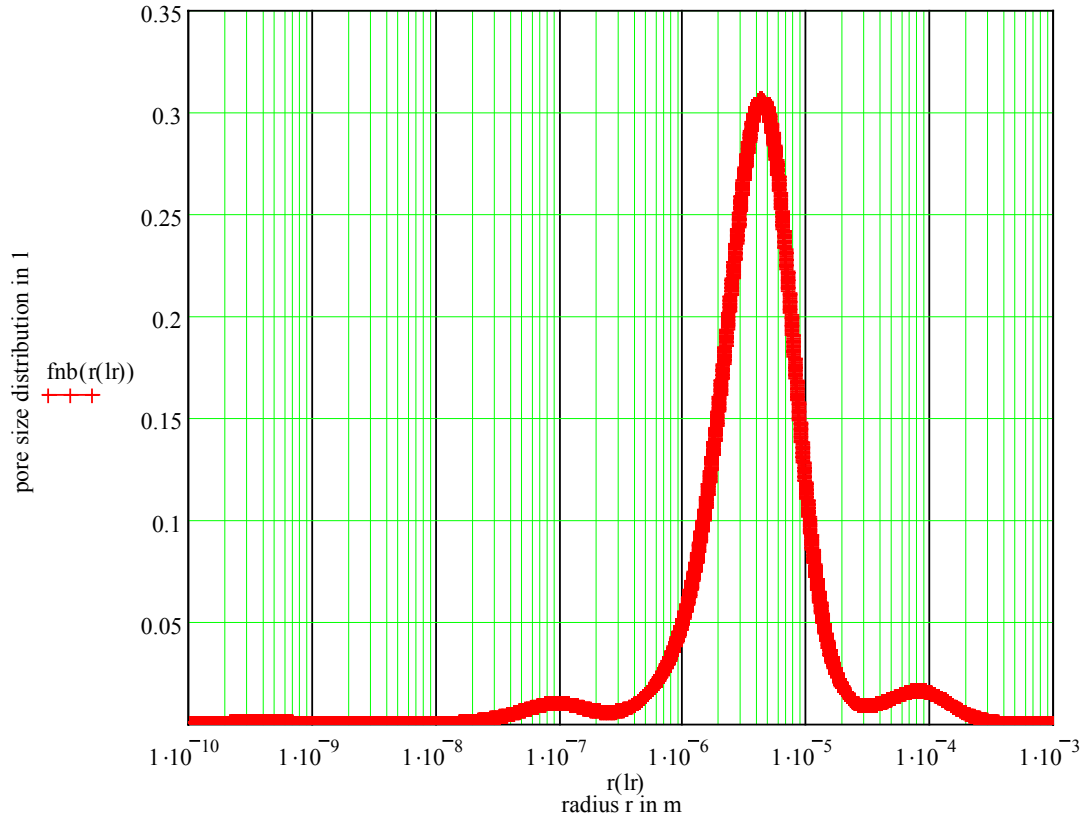


Fig. 2: Pore size distribution $fp(r)$ of the ceramic brick

4.4 Sorption isotherm $w_\phi(\phi(r))$

The sorption isotherm is the hygroscopic part of the water retention characteristic. In this function the water pressure is substituted by relative humidity by using the Kelvin-equation (4). Table 3 shows the measured values for this area.

Table 3. measured values

relative humidity (-)	moisture content w (m ³ /m ³)		relative humidity (-)	moisture content w (m ³ /m ³)
0.99998	0.2334		0.96000	0.0013
0.99985	0.2297		0.90000	0.0013
0.99956	0.0697		0.84300	0.0011
0.99852	0.0126		0.75200	0.0011
0.99705	0.0099		0.57600	0.0009
0.99411	0.0087		0.32900	0.0008
0.98971	0.0082		0.11300	0.0007
0.96900	0.0015			

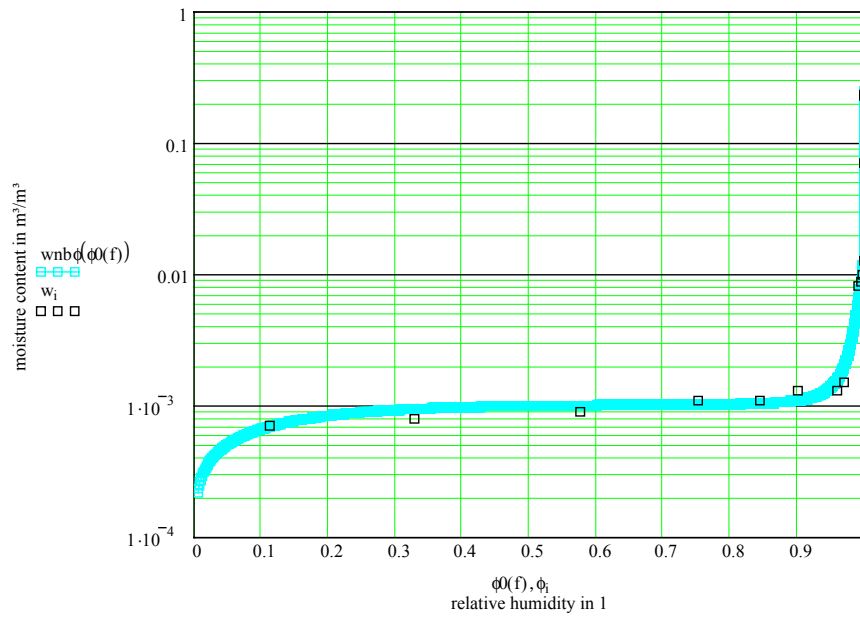


Fig. 3: Sorption isotherm $w(\phi)$

4.5 Liquid water transport functions $K_w(p_c)$ – moisture conductivity

The moisture conductivity (15) has been calculated by integration of the moisture retention function (8). Therefore the parameters are the same like function (8) (see table 2). Additionally the moisture conductivity for the saturated material (K_s – Darcy-permeability) has been used. The figures 4 and 5 show the moisture conductivities in dependence on the capillary pressure and the water content.

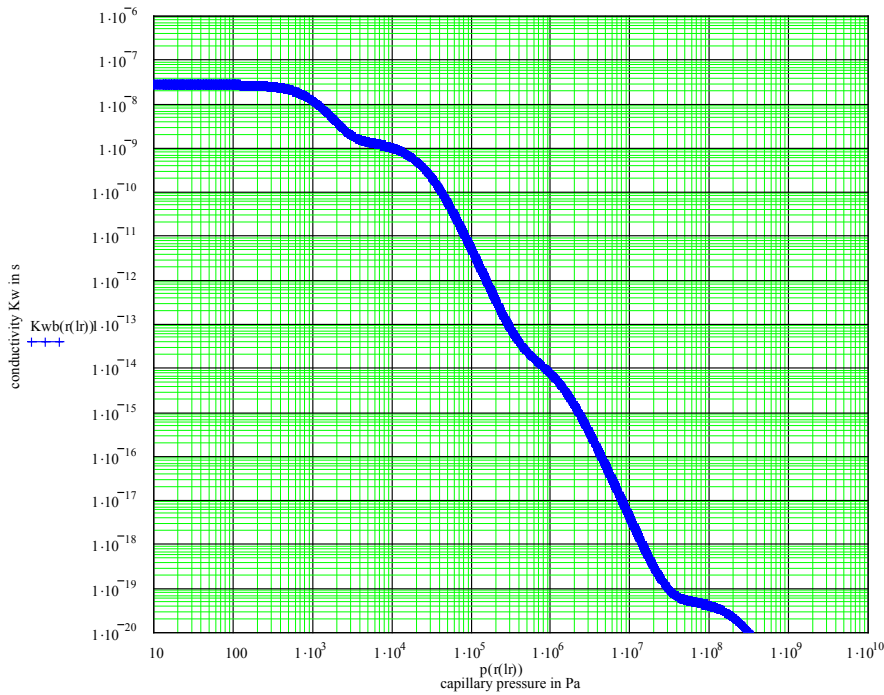


Fig. 4: Liquid water transport function $K_w(p_c)$ in dependence on capillary pressure

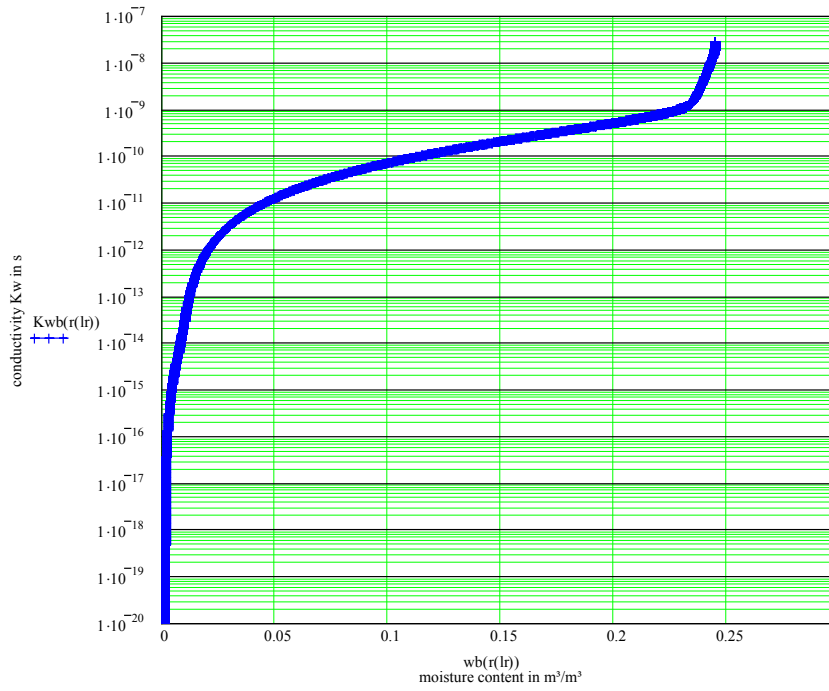


Fig. 5: Liquid water transport function $K_w(w)$ in dependence on water content

4.6 Liquid water transport function $D_w(w)$ – moisture diffusivity

The moisture diffusivity is given by (17). Figure 6 shows this function and additionally the pore size distribution (black line) in dependence on the water content. The diffusivity has a peaks (discontinuities) in areas without pores.

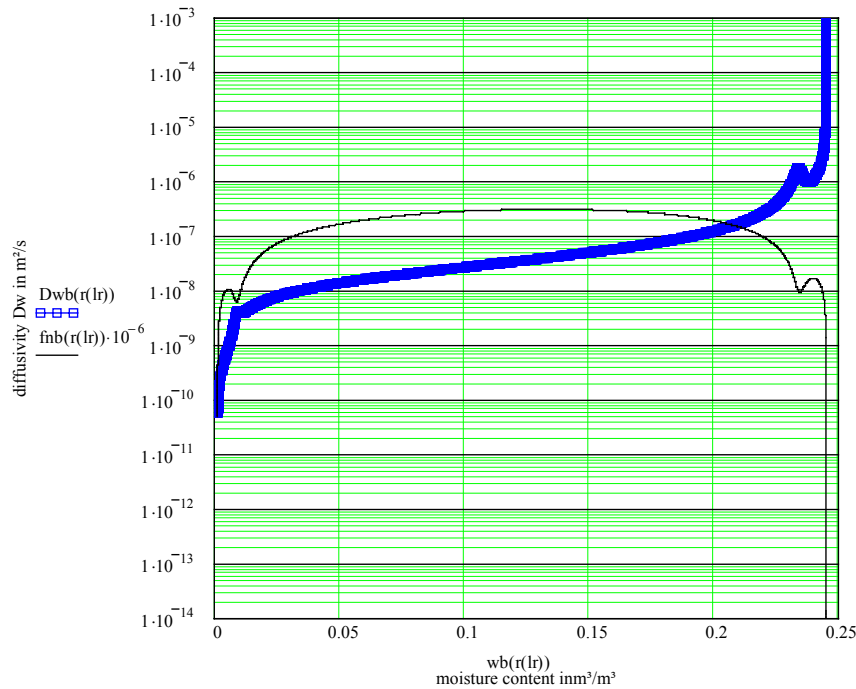


Fig. 6: Liquid water transport function $D_w(w)$ in dependence on water content – moisture diffusivity

4.7 Simplified formulation of the liquid water transport function $D_{wu}(w)$ by means of the water uptake experiments – moisture diffusivity

The parameters D_0 and k of the simplified liquid moisture transport function $D_{wu}(w)$ (21) can be determined by means of water uptake experiments. In a classical way the water uptake coefficient A_w and the water penetration coefficient B will be measured. Figure 7 shows function $D_{wu}(w)$ in comparison with $D_w(w)$ (Fig. 6).

$$\begin{aligned} A_w &= 0.146 \text{ kg/m}^2 \text{s}^{1/2} & w_{sf} &= 0.23 \text{ m}^3/\text{m}^3 \\ B &= 7.333 \cdot 10^{-4} & x_e &= 0.05 \text{ m} \\ t_e &= 4.65 \cdot 10^3 \text{ s} \end{aligned}$$

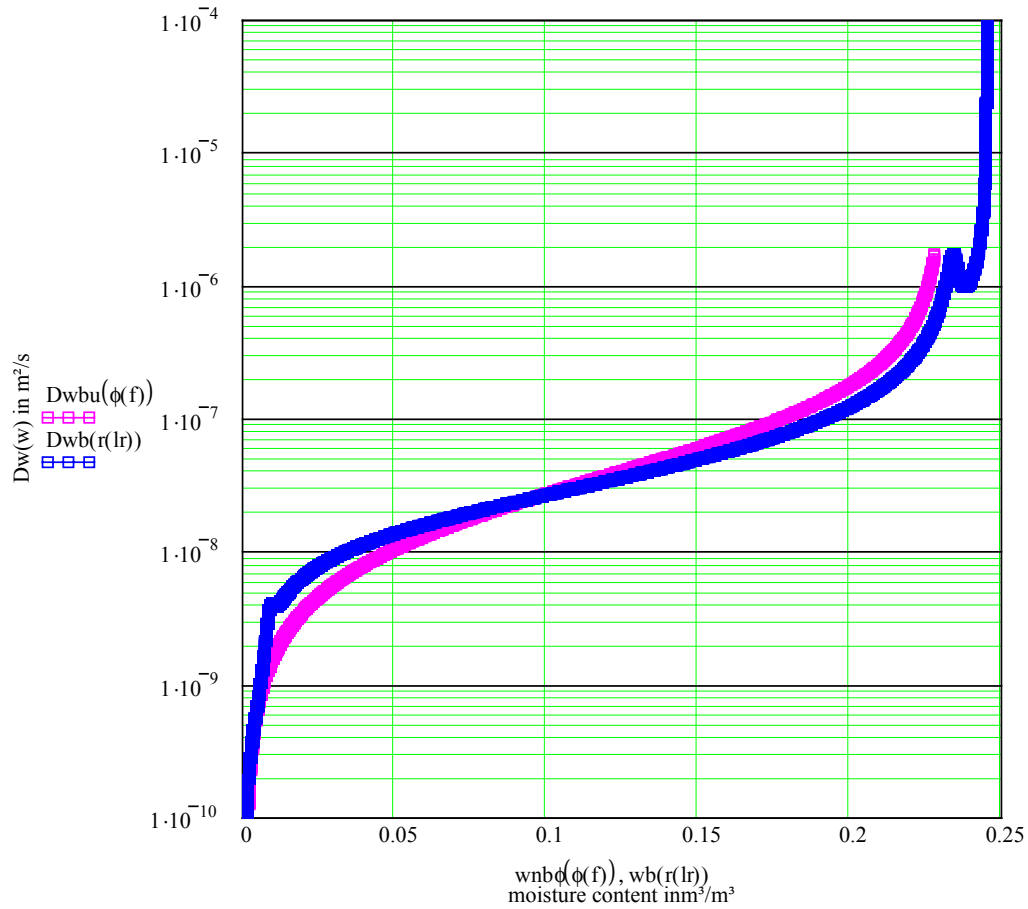


Fig. 7: Liquid water transport function $D_w(w)$ in dependence on water content – moisture diffusivity

4.8 Moisture field $w(x,t)$ in case of the direct water uptake

Figure 8 shows the moisture profiles for a water uptake experiment in a brick sample for different points in time calculated by an analytical solution of the nonlinear water transport equation (20) with $D_{wu}(w)$.

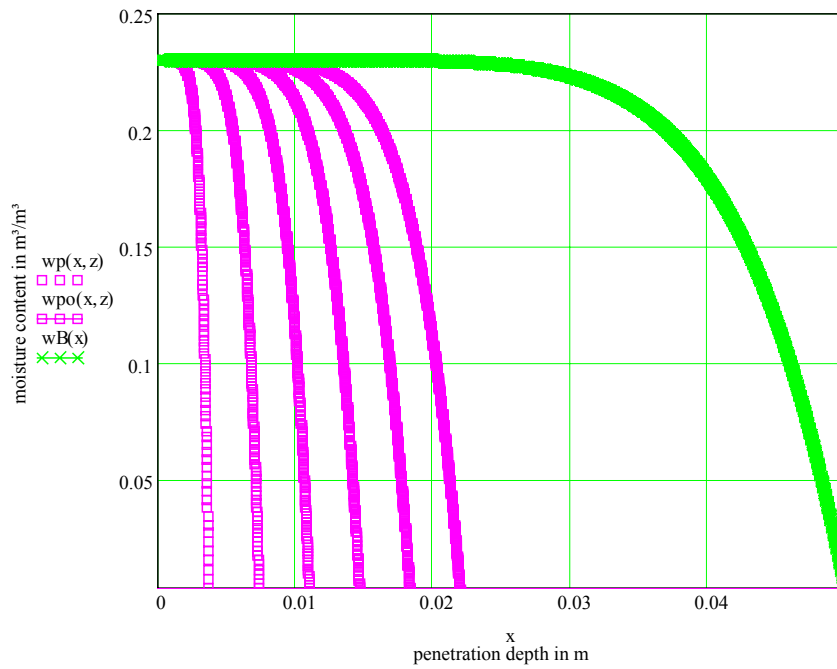


Fig. 8: Moisture profiles for time points from 25s until 900s in a ceramic brick sample for a water uptake experiment

5 SUMMARY AND CONCLUSIONS

The course of the liquid water conductivity curve can be calculated from the pore size distribution and/or the suction curve. Descriptive Parameters are the main pore diameters and the volumes of the pore compartments, i.e. 8 parameters in the case of a 4-modal formulation. For saturated specimens the conductivity must correspond with the Darcy-Permeability K_s which is also easily measurable. The result of the experiment for the determination of the „water vapour resistance coefficient“ is finally the isothermal total moisture conductivity, e.g. for relative humidities of 20% and 85%. Thus the conductivity curve can also be fixed in the low moisture range.

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With the preceding determination of the pore size distribution the overhygroscopic measurement points of the pressure plate apparatus can be placed in the plateau range of the suction curve. To investigate the transition range between hygroscopic and overhygroscopic moisture more exactly, one measurement point at $1.5 \cdot 10^6$ Pa ($\phi = 0.997667$) can be added. The moisture transport function, calculated from the moisture storage function, can be „fixed“ with justifiable (or limited) measurement expenditure.

With these eleven measurement values based on the presented model the moisture storage and moisture transport function can be determined sufficiently exact. Important is that moisture storage and moisture transport (not any more independent of each other)

can be described by relatively simple closed functions, valid in the entire moisture range. A separate empirical description of the sorption isotherm, suction curve, moisture conductivity and moisture diffusivity is not possible any more. The suggested formulas objectify the hygric material properties, facilitate the comparability and normativity of measurement procedures and provide a greater certainty for the numerical simulation of building constructions.

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